LINE FORMATION AND INTENSITY ENHANCEMENT OF THE He II 304Å LINE IN THE SOLAR ATMOSPHERE

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Abstract. Observations of He II 304Å line profiles from the Goddard solar EUV sounding rocket flight of May 9, 1991 are analyzed to determine lower limits on the small scale non-thermal velocities in the regions observed. In the quiet Sun, a lower limit of 30 km/s is obtained over much of the spectrograph slit. It is argued that a sufficient fraction of the He II ions will survive in their upward motions, before collisional excitation to produce a 304Å photon, to enhance the computed line intensity up to the observed values, in contrast to earlier theoretical results that yield total line intensities generally smaller than observed values.

Key words: Helium Emission – Transition Region – Line Formation

1. Introduction

Two problems in the formation of the He II 304Å line have long resisted a satisfactory solution: (1) determining the relative contributions of electron collisional excitation and photoionization-recombination (p-r) in populating the upper level of the transition; (2) explaining why the integrated intensity of the line computed from theoretical models of the solar atmosphere always lies a factor of two or more below observed integrated intensities. Using a unique data set obtained with the Goddard Solar Extreme Ultraviolet Telescope and Spectrograph (SERTS) flight in 1989 (SERTS-89) we were able to show that, in the quiet Sun at least, the collisional process is clearly dominant (Jordan *et al.*, 1993). From further observations obtained with SERTS-91 and reported here, we can now demonstrate that there may be adequate nonthermal motions in the lower transition region to inject enough of the He II ions upward into regions of hotter thermal electrons, and thus enhance the emission sufficiently to close the gap between theory and observations in the quiet Sun.

2. The He 304Å Line-Formation Problem and the SERTS-89 Contribution

The Helium II 304Å line is important to understanding the lower transition region of the Sun. It has long been thought to dominate the energy balance of the transition

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region between 50,000 K and 100,000 K. Recent work of Fontenla *et al.* (1993) bears directly on the question of where and how the 304Å line is formed, so we review it briefly here.

In Fontenla *et al.* (1993), a very strong case is made for the distribution of hydrogen Lyman-alpha losses over a wide temperature range just below that at which the Helium 304Å line begins to dominate the radiative energy balance. Their work solves the problem posed by the old, somewhat artificial "temperature plateau" from which most hydrogen losses were formerly thought to occur, by replacing this plateau with a distribution of neutral hydrogen atoms over a larger temperature range, a distribution they show can be caused by ambipolar diffusion of the hydrogen neutrals and ions. The consequence is that the energy of thermal conduction down from the overlying hot corona is transformed into ionization energy of ionized neutrals, which then both transport some of this energy downward and radiate the rest away over this broad temperature range, a physically self-consistent picture, which the old "plateau" model was not, and one that produces theoretical profiles for hydrogen Lyman-alpha that agree well with observations.

The relevance of this work to the 304Å line problem is that, in offering a reasonable solution to the problem of hydrogen Lyman-alpha formation, the mechanism of ambipolar diffusion becomes an obvious candidate for redistributing He II ions and "boosting" the computed intensity in 304Å up to observed values. Fontenla *et al.* (1993) did address this problem as well, and the answer they found was negative. While the inclusion of simultaneous ambipolar diffusion in both hydrogen and helium did generate good hydrogen Lyman-alpha profiles, the integrated intensity in the He 304Å line was still an underestimate. They found that some other effect was still needed. This sets the stage for our examination of the SERTS-91 results that follows.

The study of the SERTS-91 observations to seek a possible additional source of emission in the 304Å line begins with a result from an earlier study of the line-formation mechanism completed using observations from the SERTS-89 flight (Jordan *et al.*, 1993). In this paper, it was shown that electron collisional excitation dominates photoionization-recombination (p-r) by a very large margin in producing the 304Å line in the quiet Sun, and probably in active regions as well. This result is used in our search for an additional source of 304Å emission in the quiet Sun, in the following manner.

3. The He 304Å Line-Intensity Problem and the SERTS-91 Contribution

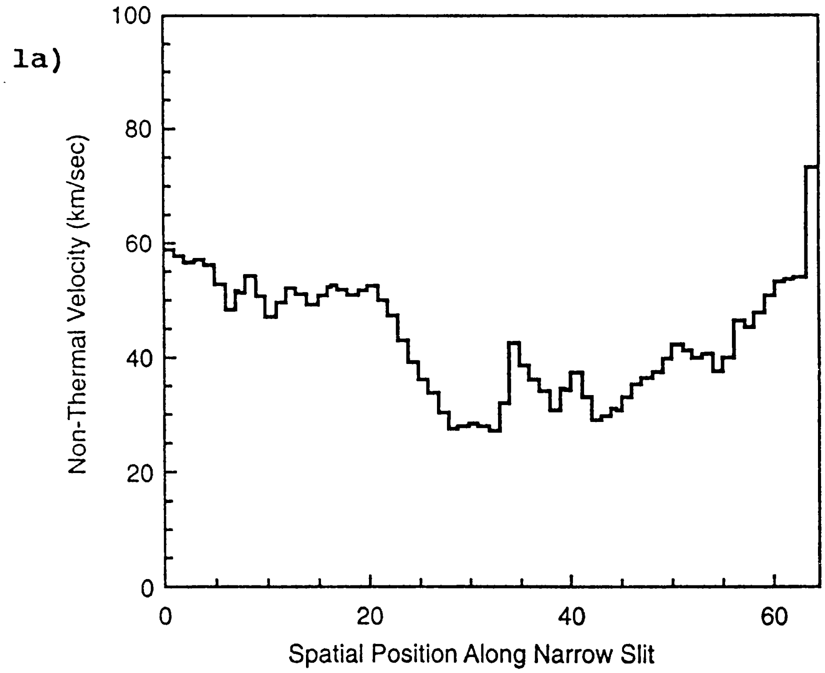
The second successful flight of the current Goddard solar sounding rocket program, SERTS-91, has yielded a set of observations well suited to addressing the discrepancy between the observed and the theoretical (computed) total intensities of the He II

304Å line. These observations may point to the solution of this problem in the quiet Sun.

The SERTS instrument features a unique "hourglass" slit that yields both wide-field images and spectra of the solar regions observed over a broad EUV spectral range (see Neupert *et al.*, 1992). Figs. 1a and 1b, respectively, are plots of the nonthermal line width and the (relative) integrated intensity along the narrow slit, taken at one of the pointing positions during the SERTS-91 flight. The narrow slit passes over active region AR 6615 in this pointing position. The nonthermal line width is expressed as a nonthermal velocity in km/s, and is the width of the line after removal of both the instrumental line width and the thermal line width at an assumed temperature of 80,000 K. One sees immediately that while the integrated intensity rises across the edge of the active region there is a corresponding drop in the nonthermal line width. The spatial resolution of these observations is 5 arc-seconds, which gives the maximum size of any unresolved nonthermal motions.

The effect of radiative transfer in an optically thick line, which we already know the 304Å line to be, is to broaden the line. Thus, most of the nonthermal broadening of the line in the active region, where the line is most intense (optically thick), may be due to radiative transfer. In this case, most of the nonthermal line width would not represent a true nonthermal velocity. However, this is definitely not the case for the line widths determined for the quiet Sun. There, the contribution of radiative transfer (optical thickness) must be less than in the active region. Yet there, in the quiet Sun, the nonthermal line width is actually much larger than in the active region by about 30 km/s, even if we assume that there is no contribution to the line broadening due to nonthermal velocity elements in the active region. It is therefore safe to say that 30 km/s represents a minimum value for the actual mean nonthermal velocity of these ions over the portion of the quiet Sun observed.

The importance of this observation is quickly appreciated when we reconsider an idea first advanced by Carole Jordan (1975) to explain the discrepancy between observed and computed 304Å intensities. We first recall the results of Jordan *et al.* (1993) that demonstrate the dominance of collisional excitation in the quiet Sun. Assuming these conditions, Jordan (1975) made use of the fact that the first process to destroy a ground-state He II ion in the transition region would be collisional excitation to the upper level of the 304Å line by thermal electrons. Jordan (1975) then estimated how far a He II ion produced in the region of non- LTE ionization equilibrium would travel upward into the transition region for a given upward component of velocity. Her method assumed a systemic mass flow of these ions, which is not the physical situation here (the SERTS-91 data reveal a negligible Doppler shift of the He 304Å line in the quiet Sun), but since the nonthermal motions we observe exceed the thermal velocities, and could represent coherent elements of up to 5 arcsec in size, a substantial transportation of He II ions from the region of their formation into regions both hotter and cooler than their formation region becomes a realistic possibility.



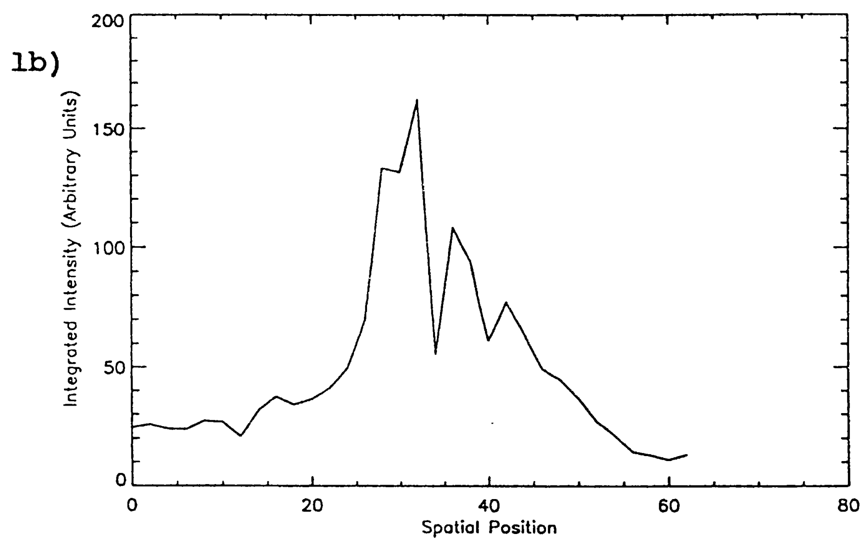


Figure 1. a – Nonthermal contribution to the He II 304Å line width, in velocity units, versus position along the narrow slit that was projected across active region AR 6615. Data point at extreme right is spurious (edge of frame). b – Relative total intensity, integrated across the line, of the 304Å line for the same slit positions illustrated in Fig. 1a. Data point at position 34 is spurious (scratch on the film), so there is probably no discontinuity at this point. Note the strong anticorrelation between intensity and nonthermal velocity.

Table 1. Computed temperatures in region penetrated

P_e=N_e T(cm^{-3} K)	dT/dh(K/km)	Upward Velocity V (km/s)			
		5	10	30	60
5.60×10^{14}	10,000	140,090	169,210	269,934	514,399
	1,000	96,052	104,478	125,376	146,511
7.50×10^{15}	25,000	103,506	114,924	143,995	175,483
	10,000	93,279	100,578	118,640	136,553

If we further take a standard (Ne, Te) model of the transition region, we can use the method developed by Jordan (1975) to estimate at what temperature the collisional excitation will take place. Table 1 gives the results of applying this procedure. Given the strong temperature dependence of the collisional excitation term, this means that only a fraction of the available He II formed at, say, 80,000 K need be transported upward by this process to greatly enhance the emission intensity. Table 2 gives the results of such an estimate.

Table 2. Intensity enhancement over 80,000 K region if half of He II ions reach region of specified T_{e2}

T_{e2} Value (K)	I_2/I_1 (304) for optically thin case
100,000	1.17
120,000	1.95
140,000	2.72
160,000	3.40
180,000	3.96
200,000	4.40

It is clear from examining Tables 1 and 2 that, for this simplified, optically thin case, intensity enhancements in the range 2-4 are not hard to achieve. A factor of 2 would bring the results of Fontenla *et al.* (1993) into agreement with the observations. No change in the ionization equilibrium situation is needed, only a change in the non-LTE source function to take into account the redistribution with height (temperature) of the dominant (collisional) source term.

4. Summary, Assessment, and Acknowledgements

Analysis of observations from the SERTS-89 sounding rocket flight demonstrates the dominance of electron collisions in the formation of the He II 304Å line in the lower transition region of the Sun, certainly in the quiet Sun, and probably in the active regions as well. Using this result for the quiet Sun, further observations made during the SERTS-91 flight are used to demonstrate that nonthermal motions on a scale up to the resolution limit of 5 arcsec may so redistribute the He II ions, that enough of them will reach a region of higher electron temperature to significantly enhance the 304Å emission, due to the strong exponential temperature dependence of the collisional source term. This may be enough to close the gap between observations and current non-LTE estimates. However, the situation in the active regions is more complex, and the same mechanism does not appear to be a good candidate there.

Since the publication of Jordan *et al.* (1993), it has come to our attention that the factor of 50 increase in our estimated coronal intensity from quiet Sun to strong active region, based on SERTS-89 observations, is exactly (and coincidently) the same factor published by Withbroe and Noyes (1977) for the increase in the coronal flux from quiet Sun to active region, based largely on Skylab observations. This gives us increased confidence in our estimates of the coronal radiation below the 228Å ionization limit of He II, which determines the strength of the p-r process in forming the 304Å line, an estimate which is based on the SERTS observations, using a method developed and explained in the Jordan *et al.* paper.

Others who contributed extensively to this work through their roles on the SERTS program include Werner Neupert, Principal Investigator (PI) of the SERTS-89 flight, Joseph Davila, PI of the SERTS-91 flight, William Thompson, responsible for reconstruction of all wide-field images from SERTS, and Roger Thomas, responsible for calibration of all narrow-slit spectra.

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